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Flight Assessment of a Data-Link-Based Navigation-Guidance Concept

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SUMMARY

With the proposed introduction of a data-link provision into the Air-Traffic-Control (ATC) system, the capability will exist to supplement the ground-air, voice (radio) link with digital, data-link information. Additionally, ATC computers could provide, via the data link, guidance information to aircraft on prespecified paths. This guidance information could then be presented to the pilot in much the same manner as conventional navigation information.

The primary objective of this study was to assess the feasibility of using 4-sec and 12-sec information updating to drive conventional cockpit-navigation-instrument formats for path-tracking guidance. This guidance concept would require minimum additional computation by the ground-based computers and only small modification to existing cockpit equipment. However, the use of constant-frequency noncontinuous data causes concern over the acceptance of automated, ground-based, navigation-guidance concepts utilizing this data link. A total of 19 tracking tasks were flown in a Navion aircraft during this study and, through the use of pilot questionnaires and performance data, the following results were obtained. From a performance standpoint, the 4-sec and 12-sec updating led to a slight degradation in path-tracking performance, relative to continuous updating. From the pilot's viewpoint, the 12-sec data interval was suitable for long path segments (greater than 2 min of flight time), but it was difficult to use on shorter segments because of higher work load and insufficient stabilization time. Overall, it was determined that the utilization of noncontinuous data for navigation was both feasible and acceptable for the prescribed task.

INTRODUCTION

With the proposed introduction of the Mode-S transponder system (providing a two-way digital data link) into the Air-Traffic-Control (ATC) system (ref. 1), the capability will exist to supplement the voice (radio) link between the pilot and the controller with a digital link, which could be interfaced in the aircraft to numerous cockpit displays. The use of this technology has the potential for reducing pilot misinterpretations of the controller's commands and clearances. The concept of supplementing the voice link with data-link information could be expanded to include automatic path guidance for aircraft on prespecified paths, where the ground-derived, path-guidance information could be displayed in the cockpit in the same manner as other conventional navigation information. The potential benefits of this concept are a reduction in the controller's work load and a reduction in pilot errors to a level no greater than that encountered in normal instrument navigation. Also, it is anticipated that little or no additional training would be required for the pilot to utilize this capability.

The primary objective of this study was to assess the feasibility of using noncontinuous, constant-frequency information to drive conventional cockpit-navigation-instrument formats for path-tracking guidance along simple, but realistic, flight paths. Since the major emphasis of this study was concerned with pilot acceptance, a flight test was conducted, rather than a simulation study, in order to provide the most realistic environment for the evaluation. Three data intervals were employed in

this study: (1) a zero time-between-update interval (continuous updating), which was used as a test base line for comparisons; (2) a 4-sec update interval, which was used to approximate a terminal-area Mode-S system; and (3) a 12-sec update interval, which was used to approximate an enroute Mode-S system. It should be noted that no processing was performed on the navigation data to remove the effects of the noncontinuous data rate. Eight different flight paths were used, all of which were variations of an expanded visual-flight-rules (VFR) airport traffic pattern. A total of 19 patterns were flown by each of four pilots with various levels of flight experience. Data were taken in the form of aircraft-position parameters and pilot questionnaires.

SYMBOLS AND ABBREVIATIONS

ALT altitude, positive upward

ATC Air Traffic Control

CDI course-deviation indicator

CRT cathode-ray tube

DME distance-measuring equipment

HERR displacement of horizontal-path-error pointer, positive to right

HSI horizontal-situation indicator

ILS instrument landing system

IMC instrument meteorological conditions

$K_1, K_2, \ldots, K_6$ system gains and constants

Mode S transponder system with provisions for two-way digital data link

VERR displacement of vertical-path-error pointer, positive upward

VFR visual flight rules

VMC visual meteorological conditions

VOR very-high-frequency omnidirectional range

XTRK perpendicular distance (error) from prescribed path segment, positive to right

YRNG remaining distance, along path, to end of path segment

ZPATH referenced vertical path height, positive upward

DESCRIPTION OF EQUIPMENT

Aircraft System

The Navion aircraft used in this study was modified into the General Aviation Digital Avionics Flight Test Facility, developed jointly by the Flight Dynamics Laboratory of Princeton University and the NASA Langley Research Center. (See ref. 2.) This facility is a fully instrumented, five-degree-of-freedom, fly-by-wire aircraft containing a digital flight computer system and interface equipment that permits the use of the position-tracking—transponder data-link system and ground-based, display-generation equipment at the Wallops Flight Center. The controls for the fly-by-wire system are located on the left side of the cockpit and, for this reason, this portion of the cockpit is used by the evaluation pilot. Additionally, the left side of the instrument panel of the aircraft has been reconfigured to allow for the use of a 5-in. monochromatic CRT as the primary flight display. (See fig. 1.) For this study, the fly-by-wire control system was such that a one-to-one relationship existed between the evaluation pilot's controls and the normal aircraft control system.

Ground-Based System

The two major portions of the ground-based system used in this study are the Aeronautical Radar Research Complex (ARRC) and the Flight Display Research System (FDRS). The ARRC provides a precision aircraft-tracking capability via a radar tracker. This system also provides a real-time, digital uplink and downlink data-transfer capability between the aircraft and the ground via a radar-transponder data system. The FDRS provides a generalized display-generation capability by using a ground-based interactive graphics computer, thereby placing the majority of the display-generation equipment on the ground, with the aircraft requiring only an antenna, a receiver, and a CRT display. The display is driven by the aircraft's derived parameters and modes downlinked by the transponder data system. A simplified block diagram of the ground-based system is given in figure 2.

DISPLAY FORMAT

General Format

The general format for the CRT display was that of a standard attitude indicator, presenting pitch- and roll-attitude information to the pilot. Simulated ILS path information could also be presented, in a conventional manner, in the form of vertical and horizontal scales and pointers. (See fig. 3.) This format is described in greater detail in reference 3.

Research Formats

Two additional display formats were used in this study, both of which were forms of the general format but with supplementary information added. Display format A, shown in figure 4, has magnetic-course (desired ground-track angle) information added. This information, in conjunction with the horizontal-path-error needle, could then be used by a pilot in much the same manner that a CDI is used for VOR navigation. Display format B contains the same information as display format A with the addition of range-to-go (similar to DME) and segment-number information. (See

fig. 5.) The segment number relates to various segments of a predefined path and will be described in a later section.

FLIGHT TASK

The pilot's flight task in this study was to navigate along a predefined path by using either display format A or B. Specifically, the task began at what would normally be the missed-approach point for an ILS approach, at which time the pilot would begin to navigate along a prespecified multisegment path. All paths were constructed so that at their termination, the aircraft would be inbound to the runway on a course intercepting with the final approach course. At this point, the display would revert back to the general format. The flight task terminated when the aircraft was established on the ILS path and was inbound to the runway. (That is, the aircraft was heading toward the runway and the ILS guidance needles were showing less than full-scale deflection.) The vertical portion of the paths used in this study was a constant 1500 ft until ILS capture.

Eight horizontal flight paths were employed in this study. Figure 6 illustrates paths 1, 3, 5, and 7. Paths 2, 4, 6, and 8 were "mirror images" of paths 1, 3, 5, and 7, respectively, reflected about the runway center line. The path-segment numbers shown in figure 6 are in descending order so that segment 1 was always the last segment reflected prior to intercepting the final approach course.

The airspeeds used during this study were between 90 and 115 knots, and the tests were conducted under VMC.

DISPLAY IMPLEMENTATION

General

The basic display design used in this study, both in appearance and implementation, was that of a simplified attitude indicator. (See fig. 3.) Like electromechanical attitude indicators of conventional design, the aircraft symbol and roll scale (0°, ±10°, ±20°, ±30°, and ±45° boxes) were fixed symbols, and the pitch scales and horizon line moved in such a manner that they would appear to be coupled to the real-world horizon. The roll-scale pointer rotated and translated so that it was always perpendicular to the horizon and centered through the fixed aircraft symbol. A sufficiently high update rate was used so that the motion of the movable symbols would appear to be continuous.

In addition to the basic attitude information, horizontal- and vertical-path-error information was presented via fixed scales and moving pointers. Path error and deviation rate were represented by the position and rate of motion of the pointers (representing the path) relative to the centers of the scale (representing the aircraft). Thus, if the vertical-scale pointer was positioned below the vertical-scale center, the aircraft was above the vertical path. Similarly, if the horizontal-scale pointer was positioned to the right of the horizontal-scale center, the aircraft was located to the left of the horizontal path.

ILS Tracking

In the ILS tracking mode, the position of the horizontal- and vertical-scale pointers relative to their respective scales was a function of the angular displacement of the aircraft relative to the runway. For the horizontal pointer, the pointer displacement was defined as

$$\mathrm{HERR} = K_3 \tan^{-1}\left(\frac{\mathrm{XTRK}}{\mathrm{YRNG}}\right)$$

where K_3 was set so that full-scale pointer deflection occurred at $\tan^{-1}\left(\frac{\mathrm{XTRK}}{\mathrm{YRNG}}\right) = \pm 2.5°$. (The movement was also limited to these values.) For the vertical pointer, the pointer displacement was defined as

$$\mathrm{VERR} = K_4 \left[\tan^{-1}\left(\frac{\mathrm{ALT}}{\mathrm{YRNG}}\right) - 3°\right]$$

where K_4 was set so that full-scale pointer deflection occurred at $\left[\tan^{-1}\left(\frac{\mathrm{ALT}}{\mathrm{YRNG}}\right) - 3°\right] = \pm 0.7°$. (This movement was also limited to these values.) This scaling is the same as that of a conventional ILS.

Path Tracking

Unlike the attitude and ILS information, where the motion of the various symbols always appeared to be continuous, three update rates were used for the path-guidance information (horizontal and vertical pointers and numeric information) when in the path-tracking mode. Continuous updating was employed to provide a basis for the qualitative and quantitative analysis of the path-tracking performance. Two noncontinuous update intervals were used, 4 sec and 12 sec, to approximate the radar—data-link rates of a Mode-S system. Of particular interest when employing noncontinuous updating would be the determination of the extent of the path-tracking degradation caused by the loss of the rate-of-change cues normally provided by continuously updated information.

Since display format B contained all the information provided in format A, only format B (fig. 5) will be discussed. Three items were added to the general format to create format B: (1) The path-segment magnetic course was displayed in the lower left corner of the display, (2) the range-to-go information displayed at the lower right corner represented the range from the aircraft to the endpoint of the segment, presented in nautical miles (n.mi.), and (3) the segment number, also at the lower right corner, was the number of the predefined path segment that the aircraft was currently tracking. As previously stated, the segment numbers were in descending order so that the last segment, which provided guidance to the extended runway center line for ILS capture, was number 1. Additionally, it should be noted that in order to alert the pilot to a segment transition, the path numeric information blinked on

and off (at approximately 2 Hz) for a 5-sec period beginning at the start of the transition.

In the path-tracking mode, the position of the horizontal- and vertical-scale pointers relative to their respective scales was a function of the linear displacement of the aircraft relative to the path segment. For the horizontal pointer, the pointer displacement was defined as

$$HERR = K_5(XTRK)$$

where K_5 was set so that full-scale pointer deflection occurred at XTRK = ±1/4 n.mi. for the continuous and 4-sec update intervals. For the 12-sec case, the full-scale deflection was ±3/8 n.mi. because prior simulation showed that the 1/4-n.mi. deflection was too sensitive at this data rate. It should be noted that K_5, for the continuous and 4-sec update intervals, produced a pointer displacement that was equivalent to an ILS displacement for YRNG = 5.7 n.mi. For the vertical pointer, the deflection was defined as

$$VERR = K_6(ALT - ZPATH)$$

where K_6 was scaled so that full-scale pointer deflection occurred at an error of ±200 ft from ZPATH for all update rates. A simplified block diagram of the display logic is given in figure 7.

TEST SUBJECTS AND TEST SEQUENCE

The four subject pilots used in this study represented a wide range of flight experience. One subject pilot was a NASA research test pilot with considerable experience in studies of advanced display concepts. The three remaining subject pilots were aerospace engineers with some general familiarity with advanced display concepts. Of these three subjects, all were rated in single-engine aircraft and two of these subjects were instrument flight rated.

The proposed testing sequence for this study, arranged by using a Latin-square technique, involved 48 data runs employing the various pilots, ground paths, data rates, and display formats. However, because of several problems and a time constraint that arose during the testing, only 19 of the initially proposed 48 data runs were completed. The actual test sequence and associated parameters are given in table I. It should be noted that prior to the flight test, sufficient practice was given to each pilot in ground-based simulation for him to become familiar with the task and display formats.

RESULTS AND DISCUSSION

Both quantitative and qualitative data were taken during this study. The quantitative data were in the form of aircraft-position parameters, and the qualitative data were in the form of pilot questionnaires (appendix A).

Quantitative Results

The quantitative analysis was based on the pilot's horizontal and vertical path-tracking performance during the numbered-segment portions of each run. This analysis was in the form of path-error mean and deviation values for each path segment. The segment path-error mean (MEAN) was simply

$$\text{MEAN} = \frac{\Sigma\ \text{XTRK}}{\text{N}}$$

where N was the number of samples. The standard deviation (DEVIATION) was determined by

$$\text{DEVIATION} = \left[\frac{\Sigma(\text{XTRK})^2}{\text{N}} - (\text{MEAN})^2\right]^{1/2}$$

The mean and deviation values of the horizontal tracking performance for each path segment of each data run are given in appendix B. It should be noted that the path-tracking errors associated with the data rates were as would be expected for this task. Also in appendix B, the mean and deviation values of each run are further grouped under the various test parameters (i.e., path, data rate, and display format).

By comparing the average of the mean and deviation values with the data rate, it can be seen that the tracking performance deteriorated slightly as the data-rate interval increased. A high statistical confidence level cannot be given to this difference, however, because of the limited number of data runs involved and the potential interrelationship of the other parameters (pilot, path, and display format). In contrast to the noted performance trend relating to the data rate, the tracking-performance analysis appears to be more favorably biased toward the 12-sec update than warranted, since posttest analysis showed a path-tracking problem associated with segment intercept angles, segment length, and data rate. It was found that the pilots used a somewhat more aggressive intercept maneuver (larger intercept angles) with the continuous and 4-sec update rates than they did with the 12-sec update rate, with the result that they completed the intercept and turned on to the path just as the next segment transition occurred. At this point, the aircraft had a turn rate and a bank angle opposite to that required for the transitioning intercept of the segment, thus leading to larger path-tracking errors for that segment than would normally be expected. By using run 5 as an example (shown in fig. 8(a)), the pilot was just completing the intercept of segment 2 as the transition to segment 1 occurred. Run 6, shown in figure 8(b), also shows the same problem along with the resulting large path errors. With the 12-sec update interval, this problem did not appear to occur since smaller intercept angles were generally used because of the uncertainty of the magnitude of the next path-error update.

Similarly, by comparing the mean and deviation values with the displayed information, the addition of the supplementary path information provided by display format B did not appear to improve the tracking performance. (In fact, the path-deviation values were generally higher with format B.) Therefore, from the standpoint of path-tracking performance, neither data rate nor supplementary path information appeared to have a major effect. However, the 4-sec and 12-sec noncontinuous path-guidance

updating led to a slight degradation in path-tracking performance. Plots of four typical horizontal-path profiles (the third run for each pilot) are given in figure 9.

An analysis of vertical-path-tracking performance is not presented because post-flight pilot debriefings and questionnaire results indicate that the vertical-error portion of the display was not used as the primary source of vertical-path information. The pilots used the vertical-path-error information in conjunction with the altimeter of the aircraft to determine the height of the vertical path. From that point on, the pilots used the altimeter as the primary source for vertical-path information, and they only occasionally used the vertical-path-error information to confirm the vertical-path altitude.

Qualitative Results

The basis for the qualitative analysis of this study was the responses noted in the general-comments section of the pilot questionnaire. The responses to the remainder of the questionnaire, which substantiate the commentary that follows, are provided in appendix C.

Data rate.- In general, it was felt that the performance achieved was as good with the 4-sec updating as with the continuously updated data. No adverse comments were noted concerning the 4-sec updating relative to continuous updating, although it was felt that continuous updating provided better rate cues. The 12-sec update interval was thought to be suitable for long path segments (or an enroute tracking task), but it was difficult to use on segments that were 2 n.mi. or shorter (less than 2-min flight time) because of higher work load and insufficient stabilization time. Additionally, it was thought that the work load was higher on the shorter segments with the 12-sec update interval.

Supplementary path information.- The general consensus with respect to the segment-number information was that, at best, it "was nice to have." The segment range-to-go information, however, was felt to border between being helpful and being mandatory for horizontal-path tracking. All pilots stated that the range-to-go information was used, to some extent, for turn anticipation. Additionally, all pilots hypothesized that with the range-to-go information and some prior knowledge of the course of the next segment, a reduction of the tracking error during segment transition could be realized.

General comments.- Most pilots commented on using the adjustable heading pointer on the HSI of the aircraft for a reminder of the desired course. Additionally, several pilots felt the error-pointer sensitivity was acceptable for IMC tasks but was probably too high for VMC flight (because they felt that too much time was required for looking at the display). One pilot also commented that the tracking task became easier once he had determined the effect of wind on maintaining the desired course. For the flight task in general, all pilots commented on the task being relatively simple and on the work load being generally low, particularly on the longer path segments. Overall, therefore, it was determined that the concept seemed both feasible and acceptable for the prescribed task (where the pilot had some knowledge of the general flight path).

CONCLUSIONS

A flight study was conducted to assess the feasibility of using noncontinuous (with constant frequency) information, as could be provided by a Mode-S transponder system (providing a two-way digital data link), to drive conventional cockpit-navigation-instrument formats for path-tracking guidance. Based largely on the qualitative results, the following conclusions are presented:

1. According to pilot commentary, with some prior knowledge of the general flight task, the concept seemed both feasible and acceptable for the prescribed task.

2. The 4-sec and 12-sec noncontinuous path-guidance updating led to a slight degradation in path-tracking performance.

3. Pilot subjective data indicated that the 12-sec update interval was suitable for long path segments (greater than 2 min flight time), but it was difficult to use on short path segments because of higher work load and insufficient stabilization time.

4. All pilots hypothesized that with the range-to-go (distance remaining on the path segment) information and some prior knowledge of the next course of the segment, the path-tracking error during segment transitions could be greatly reduced.

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APPENDIX A

PILOT QUESTIONNAIRE

I. In general, rate the tracking task (continuous data updating) relative to an ILS tracking task:

Easier		Same		More difficult		Much more difficult	

II. Were the additional data (segment number and segment range-to-go information) necessary to perform the tracking task?

Mandatory	Helpful, but not required	Not used

III. Relative to continuous data updating, rate the 4-sec updating:

No difference	Somewhat more difficult	More difficult	Extremely difficult	Unusable

IV. Relative to continuous data updating, rate the 12-sec updating:

No difference	Somewhat more difficult	More difficult	Extremely difficult	Unusable

V. General comments:

APPENDIX B

STATISTICAL ANALYSIS OF HORIZONTAL-PATH TRACKING PERFORMANCE

****************************** RUN NUMBER= 1 ******************************

PATH NUMBER= 2 DATA RATE= 0 DISPLAY FORMAT= B PILOT= 1

SEGMENT	SAMPLES	MEAN ERROR(FT)	MAXIMUM ERROR(FT)	DEVIATION(FT)
6	63	-221.90	-387.14	129.8
5	43	562.73	1102.23	398.2
4	76	439.48	1094.44	416.2
3	299	62.65	887.27	275.5
2	85	-120.33	736.43	475.8
1	59	855.56	1796.11	746.3

FOR TOTAL PATH: MEAN= 164.2(FT) DEVIATION= 498.0(FT)

****************************** RUN NUMBER= 2 ******************************

PATH NUMBER= 6 DATA RATE= 0 DISPLAY FORMAT= A PILOT= 1

SEGMENT	SAMPLES	MEAN ERROR(FT)	MAXIMUM ERROR(FT)	DEVIATION(FT)
5	76	-223.53	-974.41	165.2
4	106	-458.58	-818.14	225.7
3	342	77.92	434.54	195.5
2	77	648.13	2263.29	1171.0
1	108	-92.80	-408.22	108.1

FOR TOTAL PATH: MEAN= 1.3(FT) DEVIATION= 514.4(FT)

****************************** RUN NUMBER= 3 ******************************

PATH NUMBER= 8 DATA RATE= 12 DISPLAY FORMAT= B PILOT= 1

SEGMENT	SAMPLES	MEAN ERROR(FT)	MAXIMUM ERROR(FT)	DEVIATION(FT)
6	62	-228.07	-370.73	102.9
5	116	71.59	911.44	567.1
4	61	215.82	-1008.06	631.0
3	369	364.42	958.79	351.5
2	139	363.18	2398.21	949.2
1	96	514.84	1423.69	728.0

FOR TOTAL PATH: MEAN= 286.7(FT) DEVIATION= 608.6(FT)

****************************** RUN NUMBER= 4 ******************************

PATH NUMBER= 7 DATA RATE= 4 DISPLAY FORMAT= A PILOT= 1

SEGMENT	SAMPLES	MEAN ERROR(FT)	MAXIMUM ERROR(FT)	DEVIATION(FT)
6	62	30.64	134.51	58.6
5	140	-584.79	-1944.55	659.2
4	89	-2170.26	-3610.87	1101.2
3	387	-488.01	-2777.23	706.6
2	102	-722.90	-1883.38	645.6
1	102	-1499.19	-3078.11	1203.3

FOR TOTAL PATH: MEAN= -780.8(FT) DEVIATION= 983.7(FT)

****************************** RUN NUMBER= 5 ******************************

PATH NUMBER= 5 DATA RATE= 4 DISPLAY FORMAT= B PILOT= 1

SEGMENT	SAMPLES	MEAN ERROR(FT)	MAXIMUM ERROR(FT)	DEVIATION(FT)
5	73	-140.58	-387.14	174.9
4	129	-25.01	716.43	141.9
3	329	-80.28	487.38	174.3
2	70	-2107.68	-3611.71	1192.6
1	109	-727.06	-2729.03	1265.3

FOR TOTAL PATH: MEAN= -375.6(FT) DEVIATION= 887.0(FT)

****************************** RUN NUMBER= 6 ******************************

PATH NUMBER= 1 DATA RATE= 0 DISPLAY FORMAT= B PILOT= 2

SEGMENT	SAMPLES	MEAN ERROR(FT)	MAXIMUM ERROR(FT)	DEVIATION(FT)
6	78	-73.95	-180.45	74.3
5	47	-710.91	-1109.20	307.5
4	84	-498.92	-1455.33	582.4
3	296	-49.50	-1602.49	505.9
2	90	-2048.26	-3597.33	1052.0
1	69	-1595.28	-2633.32	776.0

FOR TOTAL PATH: MEAN= -587.6(FT) DEVIATION= 965.2(FT)

****************************** RUN NUMBER= 7 ******************************

PATH NUMBER= 4 DATA RATE= 0 DISPLAY FORMAT= A PILOT= 2

SEGMENT	SAMPLES	MEAN ERROR(FT)	MAXIMUM ERROR(FT)	DEVIATION(FT)
7	70	14.90	124.67	49.5
6	81	553.84	1558.51	608.2
5	89	-30.84	736.81	404.7
4	225	-6.57	923.59	316.6
3	69	871.42	2106.85	862.7
2	34	656.63	1046.84	325.2
1	38	1124.28	1588.16	384.5

FOR TOTAL PATH: MEAN= 275.3(FT) DEVIATION= 603.4(FT)

****************************** RUN NUMBER= 8 ******************************

PATH NUMBER= 5 DATA RATE= 4 DISPLAY FORMAT= A PILOT= 2

SEGMENT	SAMPLES	MEAN ERROR(FT)	MAXIMUM ERROR(FT)	DEVIATION(FT)
5	94	47.78	731.63	129.1
4	113	514.79	939.53	268.1
3	313	-126.35	-749.50	244.3
2	54	-540.84	-770.50	232.4
1	115	-581.54	-1511.96	513.5

FOR TOTAL PATH: MEAN= -105.9(FT) DEVIATION= 456.3(FT)

****************************** RUN NUMBER= 9 ******************************

PATH NUMBER= 3 DATA RATE= 12 DISPLAY FORMAT= A PILOT= 2

SEGMENT	SAMPLES	MEAN ERROR(FT)	MAXIMUM ERROR(FT)	DEVIATION(FT)
7	73	-9.17	131.23	86.1
6	74	-685.40	-1800.43	777.7
5	78	279.48	811.38	544.2
4	224	-213.08	-1412.43	425.7
3	72	-1206.91	-2129.43	872.6
2	31	-169.77	-486.46	271.0
1	46	-414.19	-1516.74	745.2

FOR TOTAL PATH: MEAN= -315.3(FT) DEVIATION= 702.2(FT)

****************************** RUN NUMBER= 10 ******************************

PATH NUMBER= 5 DATA RATE= 4 DISPLAY FORMAT= B PILOT= 2

SEGMENT	SAMPLES	MEAN ERROR(FT)	MAXIMUM ERROR(FT)	DEVIATION(FT)
5	96	6.39	508.53	98.3
4	117	219.40	565.51	232.6
3	306	-271.76	-1461.44	343.6
2	72	-3028.59	-4202.26	1007.3
1	125	-529.07	-1804.56	616.1

FOR TOTAL PATH: MEAN= -476.4(FT) DEVIATION=1005.9(FT)

****************************** RUN NUMBER= 11 ******************************

PATH NUMBER= 6 DATA RATE= 12 DISPLAY FORMAT= B PILOT= 2

SEGMENT	SAMPLES	MEAN ERROR(FT)	MAXIMUM ERROR(FT)	DEVIATION(FT)
5	97	56.72	147.64	50.7
4	138	-266.69	1058.50	557.1
3	296	86.42	-736.72	251.2
2	55	2033.51	2729.17	656.5
1	113	88.78	1351.50	614.4

FOR TOTAL PATH: MEAN= 166.2(FT) DEVIATION= 706.4(FT)

****************************** RUN NUMBER= 12 ******************************

PATH NUMBER= 6 DATA RATE= 0 DISPLAY FORMAT= B PILOT= 4

SEGMENT	SAMPLES	MEAN ERROR(FT)	MAXIMUM ERROR(FT)	DEVIATION(FT)
5	100	-35.50	-833.33	164.7
4	126	-1183.09	-1543.20	262.1
3	321	275.12	1176.01	261.5
2	NOTE: RADAR TRACKING LOST INTERMITTENTLY THROUGHOUT SEGMENT			
1	134	454.20	2652.87	1040.2

FOR TOTAL PATH: MEAN= -1.7(FT) DEVIATION= 776.6(FT)

NOTE: RADAR TRACK LOST INTERMITTENTLY THROUGHOUT RUN, DATA NOT USED IN STATISTICAL SUMMARY.

****************************** RUN NUMBER= 13 ******************************

PATH NUMBER= 5 DATA RATE= 0 DISPLAY FORMAT= A PILOT= 4

SEGMENT	SAMPLES	MEAN ERROR(FT)	MAXIMUM ERROR(FT)	DEVIATION(FT)
5	97	-33.52	-488.85	143.0
4	136	-196.85	-1521.10	575.2
3	314	-265.65	-870.89	244.6
2	58	-1427.12	-1725.23	385.7
1	RADAR TRACKING LOST			

FOR TOTAL PATH: MEAN= -324.3(FT) DEVIATION= 508.0(FT)

****************************** RUN NUMBER= 14 ******************************

PATH NUMBER= 4 DATA RATE= 12 DISPLAY FORMAT= B PILOT= 4

SEGMENT	SAMPLES	MEAN ERROR(FT)	MAXIMUM ERROR(FT)	DEVIATION(FT)
7	72	15.31	91.86	55.5
6	86	944.19	2119.80	769.6
5	88	-110.36	812.15	521.6
4	232	-37.11	1310.72	438.0
3	82	3002.43	4125.36	1028.8
2	46	1770.94	2320.34	475.1
1	40	477.84	962.52	369.5

FOR TOTAL PATH: MEAN= 635.8(FT) DEVIATION=1200.3(FT)

****************************** RUN NUMBER= 15 ******************************

PATH NUMBER= 1 DATA RATE= 4 DISPLAY FORMAT= A PILOT= 4

SEGMENT	SAMPLES	MEAN ERROR(FT)	MAXIMUM ERROR(FT)	DEVIATION(FT)
6	78	-29.32	-104.99	52.8
5	51	-554.86	-874.91	209.7
4	83	-344.51	-1140.37	538.3
3	276	-259.55	-946.32	254.8
2	80	-1824.03	-2704.94	784.8
1	63	-1473.77	-2334.59	650.9

FOR TOTAL PATH: MEAN= -585.7(FT) DEVIATION= 745.0(FT)

****************************** RUN NUMBER= 16 ******************************

PATH NUMBER= 3 DATA RATE= 12 DISPLAY FORMAT= A PILOT= 3

SEGMENT	SAMPLES	MEAN ERROR(FT)	MAXIMUM ERROR(FT)	DEVIATION(FT)
7	73	78.25	295.28	83.3
6	78	-1450.01	-2661.77	891.9
5	78	-675.45	-1416.70	693.8
4	230	-279.91	-1688.02	522.1
3	79	-1669.15	-2634.01	791.7
2	RADAR TRACKING LOST			
1	RADAR TRACKING LOST			

FOR TOTAL PATH: MEAN= -662.3(FT) DEVIATION= 876.2(FT)

NOTE: RADAR TRACK LOST INTERMITTENTLY THROUGHOUT RUN, DATA NOT USED IN STATISTICAL SUMMARY.

****************************** RUN NUMBER= 17 ******************************

PATH NUMBER= 7 DATA RATE= 4 DISPLAY FORMAT= A PILOT= 3

SEGMENT	SAMPLES	MEAN ERROR(FT)	MAXIMUM ERROR(FT)	DEVIATION(FT)
6	71	54.62	236.22	70.5
5	134	-255.29	-1414.73	532.0
4	80	-2554.21	-3977.41	1028.6
3	357	-711.29	-2448.85	568.8
2	127	-439.06	-1331.24	435.5
1	108	-575.93	-2403.00	979.7

FOR TOTAL PATH: MEAN= -691.6(FT) DEVIATION= 903.8(FT)

NOTE: RADAR TRACK LOST INTERMITTENTLY THROUGHOUT RUN, DATA NOT USED IN STATISTICAL SUMMARY.

****************************** RUN NUMBER= 18 ******************************

PATH NUMBER= 5 DATA RATE= 4 DISPLAY FORMAT= B PILOT= 3

SEGMENT	SAMPLES	MEAN ERROR(FT)	MAXIMUM ERROR(FT)	DEVIATION(FT)
5	95	-6.53	406.82	86.5
4	116	96.04	782.05	328.4
3	303	-520.89	-2366.96	844.8
2	81	-3333.41	-5032.31	1026.3
1	146	-1481.53	-4180.38	1563.1

FOR TOTAL PATH: MEAN= -855.1(FT) DEVIATION=1389.7(FT)

NOTE: RADAR TRACK LOST INTERMITTENTLY THROUGHOUT RUN, DATA NOT USED IN STATISTICAL SUMMARY.

****************************** RUN NUMBER= 19 ******************************

PATH NUMBER= 5 DATA RATE= 0 DISPLAY FORMAT= B PILOT= 3

SEGMENT	SAMPLES	MEAN ERROR(FT)	MAXIMUM ERROR(FT)	DEVIATION(FT)
5	98	-20.02	521.65	125.9
4	117	188.38	827.98	348.9
3	320	-778.84	-3987.69	1282.7
2	57	-909.39	-1357.77	397.0
1	133	-584.97	-2269.24	838.7

FOR TOTAL PATH: MEAN= -494.9(FT) DEVIATION=1021.6(FT)

NOTE: RADAR TRACK LOST INTERMITTENTLY THROUGHOUT RUN, DATA NOT USED IN STATISTICAL SUMMARY.

APPENDIX B

RUN MEAN AND DEVIATION VALUES BY DATA RATE

	MEAN (ABSOLUTE-FT)	DEVIATION (FT)
** DATA RATE = 0 **		
	164.2	498.0
	1.3	514.4
	587.6	965.2
	275.3	603.4
	1.7	776.6
	324.3	508.0
	------	------
AVERAGES:	225.8	690.6
** DATA RATE = 4 **		
	178.8	983.7
	375.6	887.0
	105.9	456.3
	476.4	1005.9
	585.7	745.0
	------	------
AVERAGES:	344.5	815.6
** DATA RATE = 12 **		
	286.7	608.6
	315.3	702.2
	166.2	706.4
	635.8	1200.3
	------	------
AVERAGES:	351.0	804.4

APPENDIX B

RUN MEAN AND DEVIATION VALUES BY DISPLAY FORMAT

	MEAN (ABSOLUTE-FT)	DEVIATION (FT)
** DISPLAY FORMAT = A **		
	1.3	514.4
	78.8	983.7
	275.3	603.4
	105.9	456.3
	315.3	702.2
	324.3	508.0
	585.7	745.0
	------	------
AVERAGES:	240.9	644.7
** DISPLAY FORMAT = B **		
	164.2	498.0
	286.7	608.6
	375.6	887.0
	587.6	965.2
	476.4	1005.9
	166.2	706.4
	1.7	776.6
	635.8	1200.3
	------	------
AVERAGES:	336.8	831.0

APPENDIX C

QUESTIONNAIRE RESPONSE

The following results are the normalized values of the pilot responses to the questionnaire of appendix A:

I. The ratings of the tracking task (continuous data updating) relative to an ILS tracking task:

Easier		Same		More difficult		Much more difficult	
	40%	60%					

II. The ratings as to whether the additional data (segment number and segment range-to-go information) were necessary to perform the tracking task:

Mandatory	Helpful, but not required	Not used
20%	80%	

III. The ratings of the 4-sec update interval relative to continuous updating:

No difference	Somewhat more difficult	More difficult	Extremely difficult	Unusable
60%	40%			

IV. The ratings of the 12-sec update interval relative to continuous updating:

No difference	Somewhat more difficult	More difficult	Extremely difficult	Unusable
	40%	60%		

REFERENCES

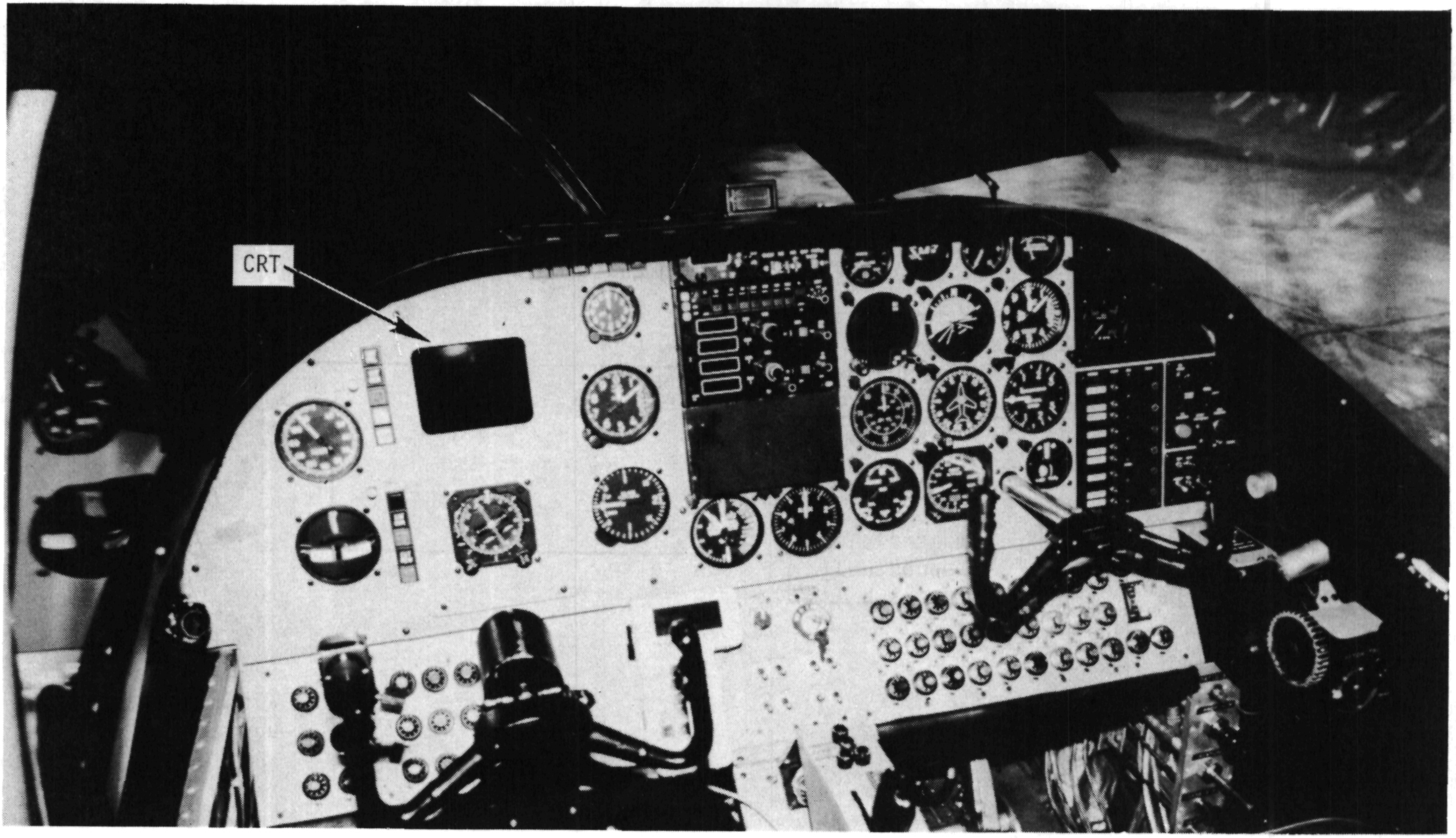
1. National Airspace System Plan - Facilities, Equipment and Associated Development. FAA, Dec. 1981.

2. Downing, D. R.; Bryant, W. H.; and Stengel, R. F.: NASA/Princeton Digital Avionics Flight Test Facility. Challenge of the '80s - 3rd Digital Avionics Systems Conference, IEEE, Nov. 1979, pp. 70-75.

3. Downing, D. R.; Bryant, W. H.; and Yenni, K. R.: Flight Test Evaluation of Advanced Symbology for General Aviation Approach to Landing Displays. AIAA-81-1643, Aug. 1981.

TABLE I.- TEST SEQUENCE

Run	Path	Data rate	Display option	Pilot
1	2	0	B	1
2	6	0	A	1
3	8	12	B	1
4	7	4	A	1
5	5	4	B	1
6	1	0	B	2
7	4	0	A	2
8	5	4	A	2
9	3	12	A	2
10	5	4	B	2
11	6	12	B	2
12	6	0	B	4
13	5	0	A	4
14	4	12	B	4
15	1	4	A	4
16	3	12	A	3
17	7	4	A	3
18	5	4	B	3
19	5	0	B	3



L-81-10,781.1

Figure 1.- Instrument panel of research aircraft.

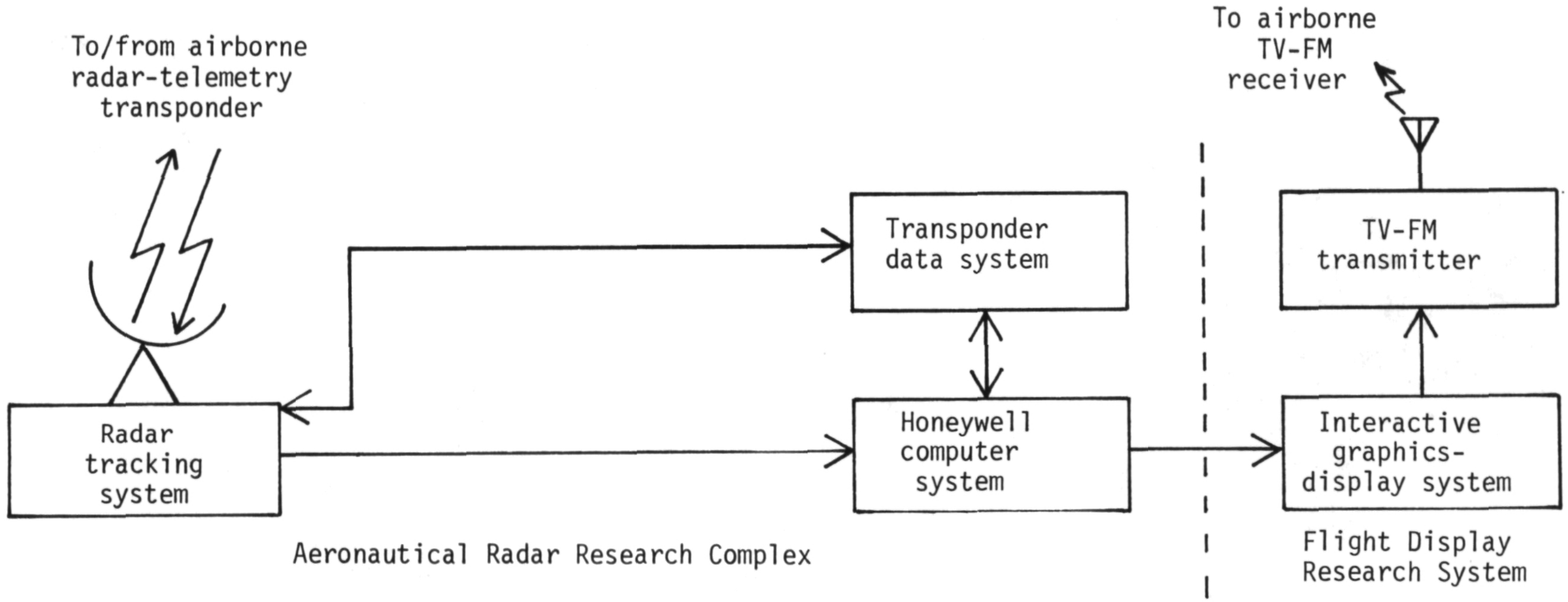


Figure 2.- Simplified block diagram of ground-based system.

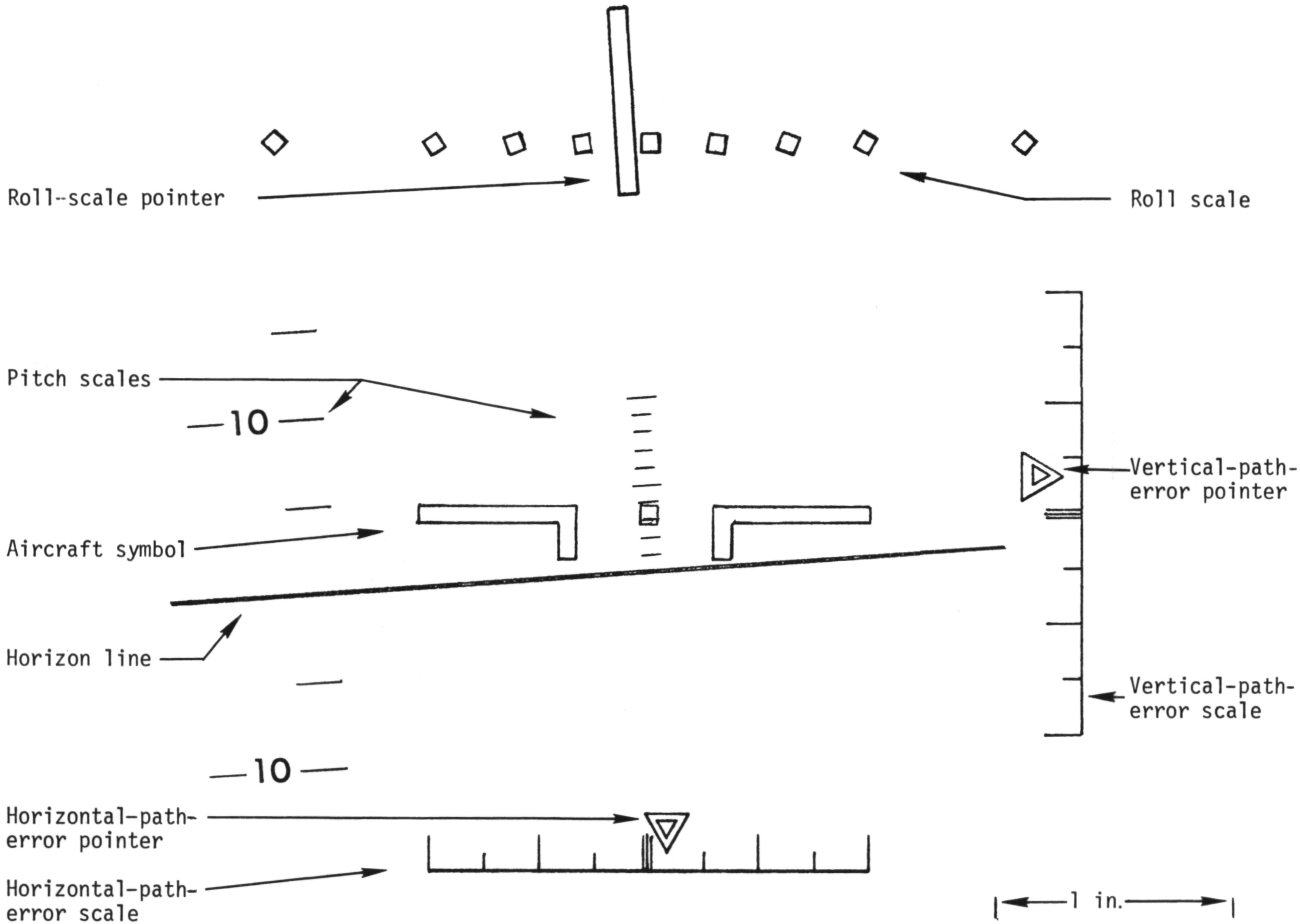


Figure 3.- General display format.

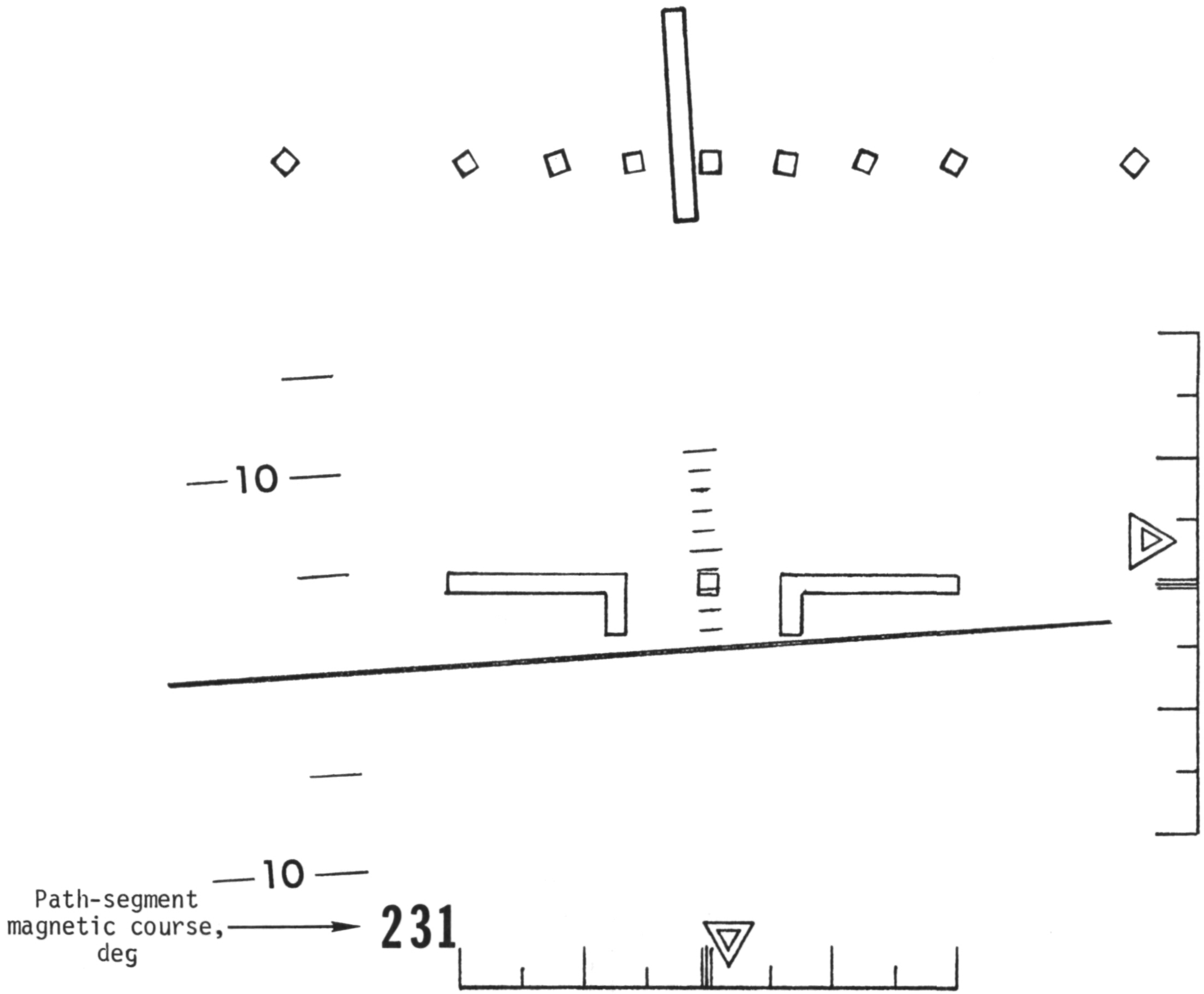


Figure 4.- Display format A.

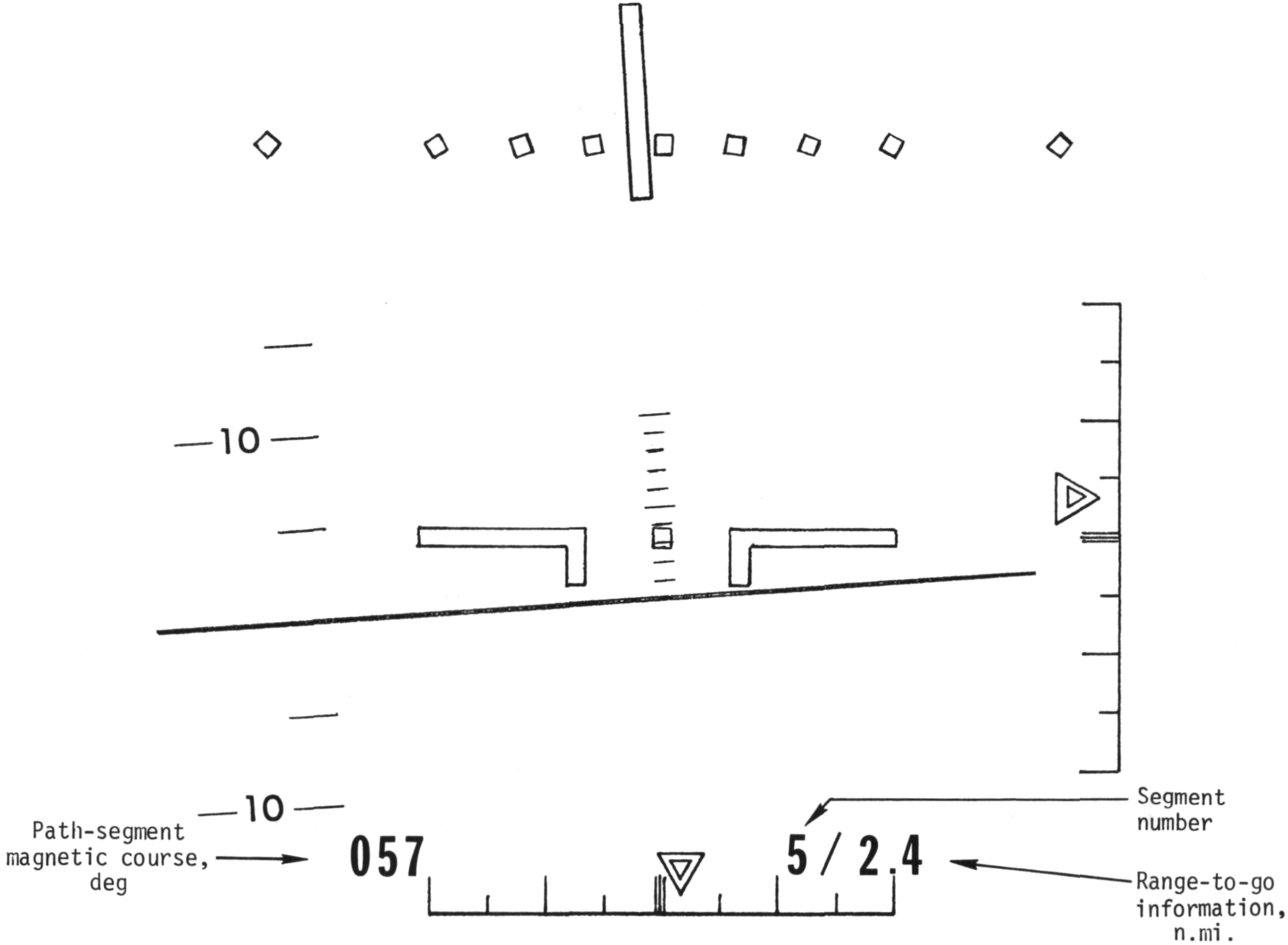
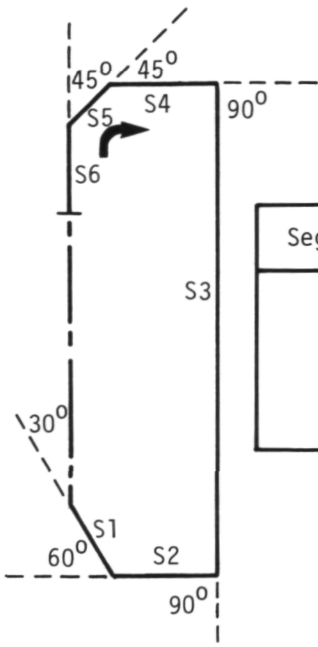
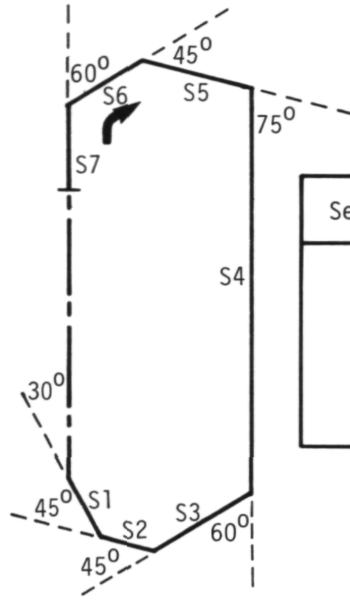


Figure 5.- Display format B.



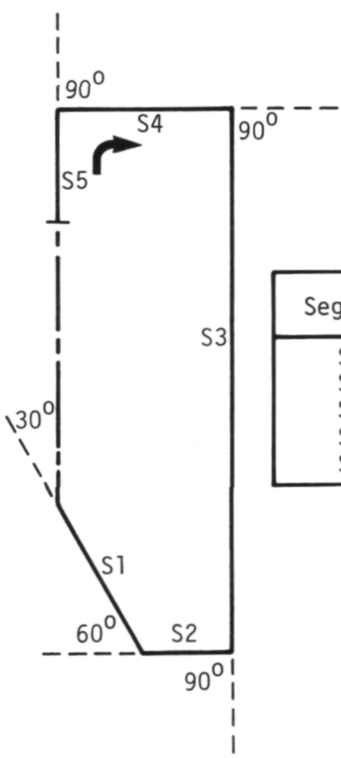
Segment	Length, n.mi.
S1	1.5
S2	2.0
S3	8.5
S4	2.0
S5	1.0
S6	1.5

(a) Path 1.



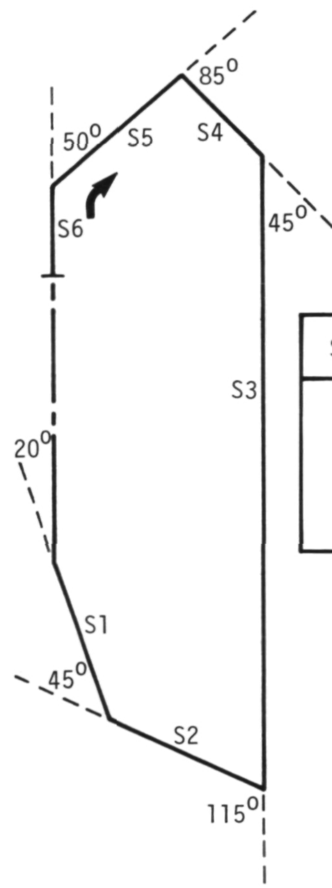
Segment	Length, n.mi.
S1	1.0
S2	1.0
S3	2.0
S4	7.0
S5	2.0
S6	1.5
S7	1.5

(b) Path 3.



Segment	Length, n.mi.
S1	3.0
S2	1.5
S3	9.5
S4	3.0
S5	2.0

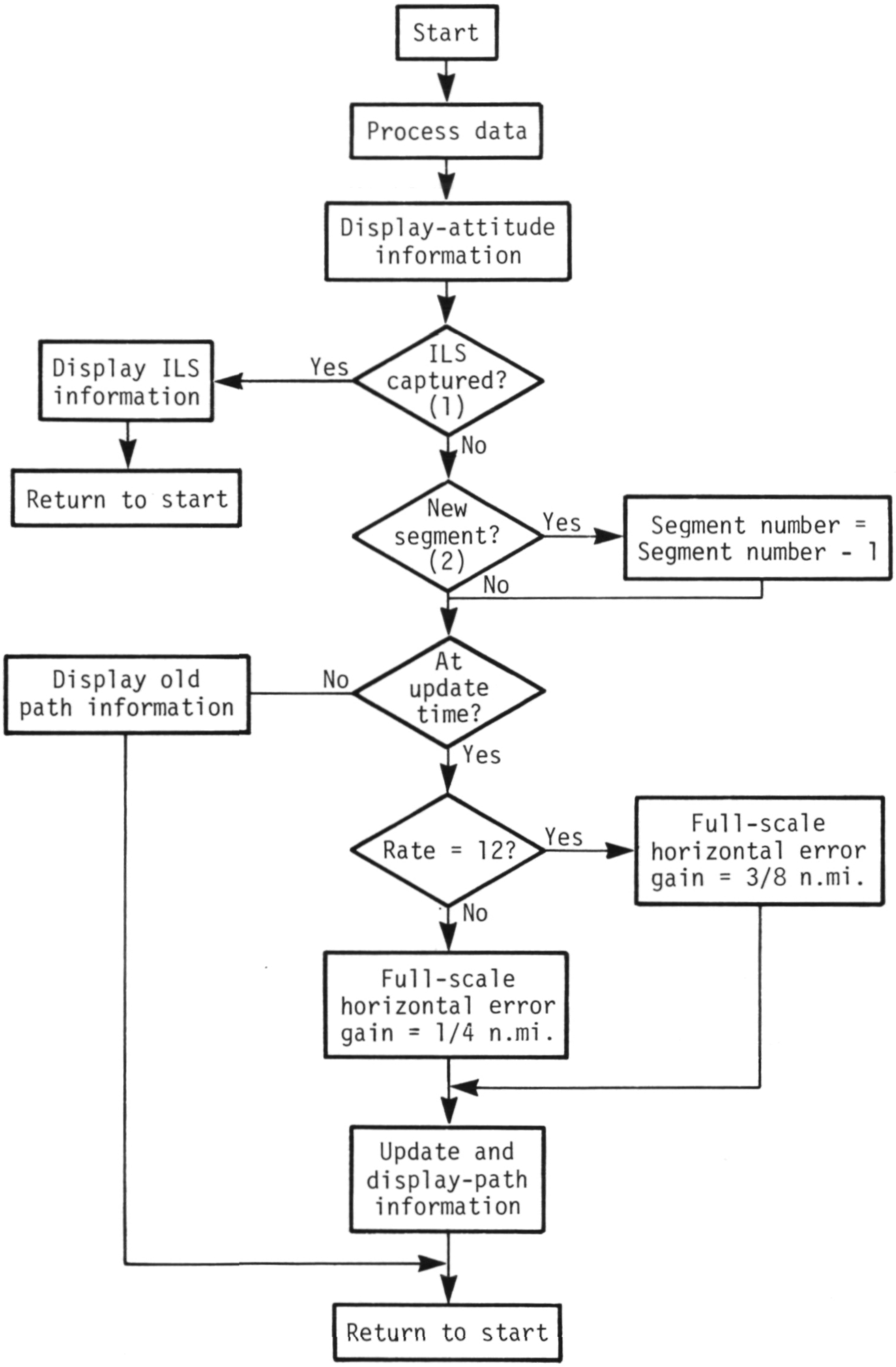
(c) Path 5.



Segment	Length, n.mi.
S1	2.5
S2	3.0
S3	11.0
S4	2.0
S5	3.0
S6	1.5

(d) Path 7.

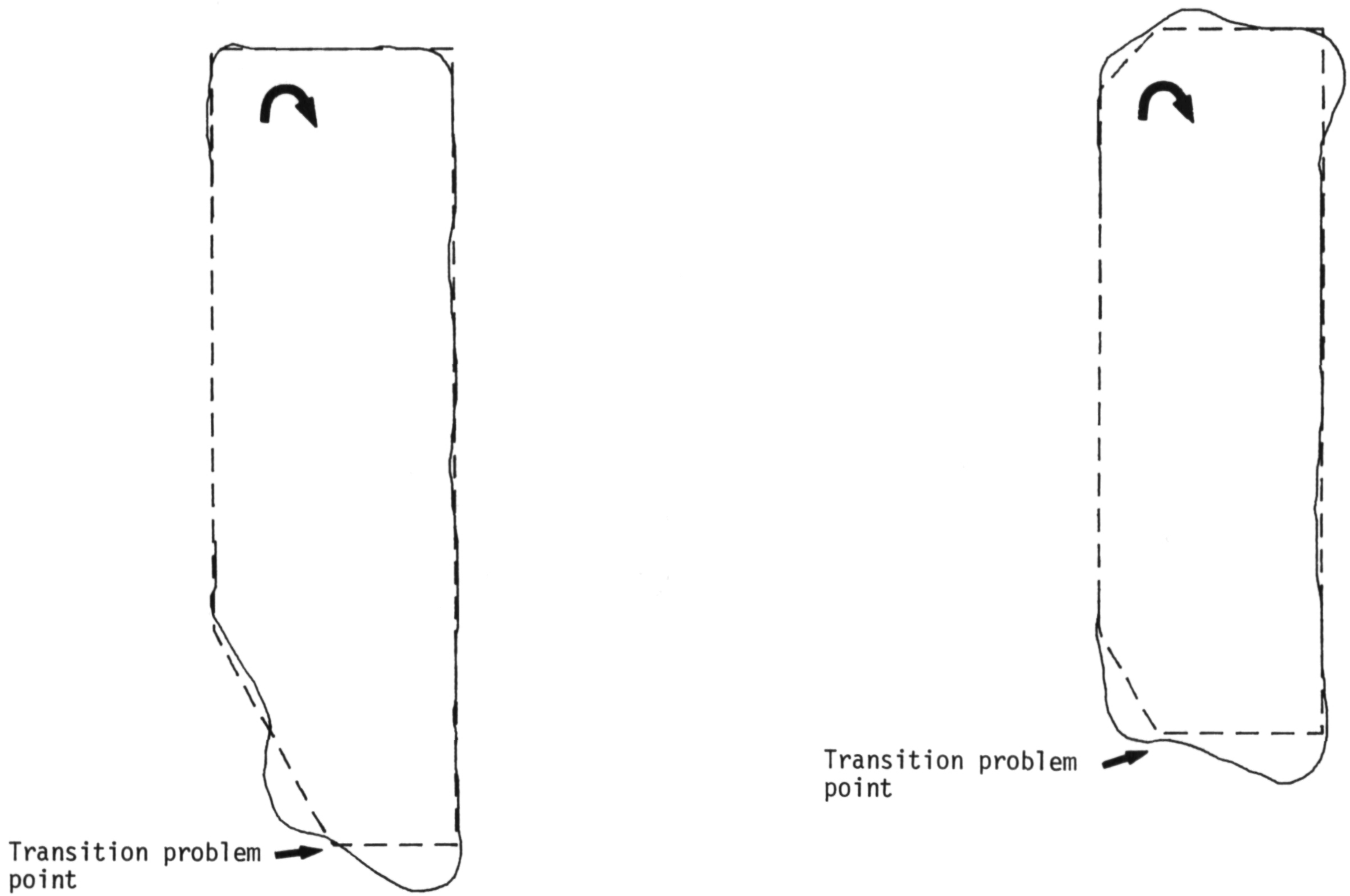
Figure 6.- Horizontal flight paths. Path segments are denoted by an "S" and the number of the segment. All path lengths are approximate to the nearest 0.5 n.mi. Arrows indicate direction of flight.



(1) Switch to true if on last segment, ILS is valid, and distance remaining on last segment is less than 0.5 n.mi.

(2) Switch to true if the distance remaining on the segment is less than K_1 (update rate + K_2).

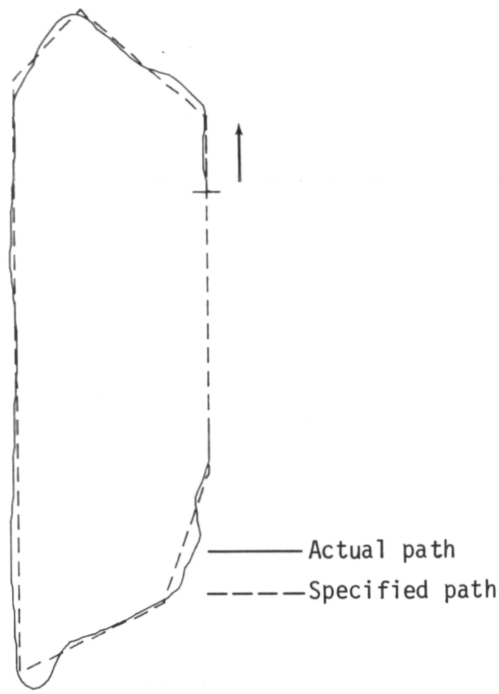
Figure 7.- Block diagram of display logic.



(a) Run 5.

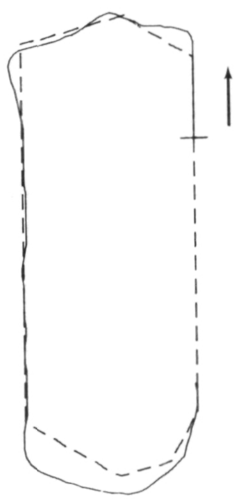
(b) Run 6.

Figure 8.- Horizontal profiles of runs 5 and 6. Arrows indicate direction of flight.

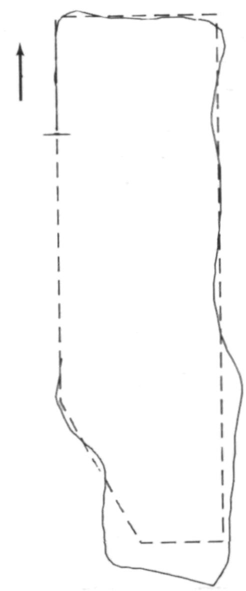


(a) Run 3. 12-sec update rate and display format B.

(b) Run 8. 4-sec update rate and display format A.



(c) Run 14. 4-sec update rate and display format B.



(d) Run 18. 4-sec update rate and display format B. Intermittent radar tracking problems.

Figure 9.- Four typical horizontal-path profiles (third run for each pilot). Arrows indicate direction of flight.

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16. Abstract

With the proposed introduction of a data-link provision into the Air-Traffic-Control (ATC) system, the capability will exist to supplement the ground-air, voice (radio) link with digital, data-link information. Additionally, ATC computers could provide, via the data link, guidance and navigation information to the pilot which could then be presented in much the same manner as conventional navigation information. The primary objective of this study was to assess the feasibility and acceptability of using 4-sec and 12-sec information updating to drive conventional cockpit-navigation-instrument formats for path-tracking guidance. A flight test, consisting of 19 tracking tasks, was conducted and, through the use of pilot questionnaires and performance data, the following results were obtained. From a performance standpoint, the 4-sec and 12-sec updating led to a slight degradation in path-tracking performance, relative to continuous updating. From the pilot's viewpoint, the 12-sec data interval was suitable for long path segments (greater than 2 min of flight time), but it was difficult to use on shorter segments because of higher work load and insufficient stabilization time. Overall, it was determined that the utilization of noncontinuous data for navigation was both feasible and acceptable for the prescribed task.

17. Key Words (Suggested by Author(s))
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